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A THERMAL SYSTEM FOR CONTINUOUS MONITORING OF LAMINAR AND TURBULENT BOUNDARY-LAYER FLOWS DURING ROUTINE FLIGHT

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A THERMAL SYSTEM FOR CONTINUOUS MONITORING OF LAMINAR AND TURBULENT BOUNDARY-LAYER FLOWS DURING ROUTINE FLIGHT

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SUMMARY

A thermal system has been developed which could be used to determine whether the boundary layer on a wing in flight is turbulent or laminar. This system, when used in conjunction with continuous recording instruments such as the galvanometer in an NACA VGH recorder and a motor-driven selector switch, would permit continuous monitoring of the boundary layer during routine flight with little or no attention from the crew. Detection is based on the difference in rate of heat transfer to a turbulent boundary layer as compared with that to a laminar boundary layer. The detectors, which consist of insulated resistance-thermometer gages cemented to the wing surface, combine the functions of heating and temperature measurement. Wind-tunnel tests indicate that a usable signal is obtained when the Reynolds number per foot is about 0.15×10^6 or greater. If the detectors can be matched well enough and the gage temperature increased, they may be feasible for use at somewhat lower Reynolds numbers.

INTRODUCTION

Recent developments in aircraft design have made flight at very high altitudes a reality. At these altitudes, the Reynolds number is sufficiently low that, by giving careful attention to the wing surface finish, rather large extents of laminar flow may be obtained. For this reason, it would be desirable to have a method of surveying the condition of the boundary layer on such a wing during flight to determine the extent of laminar flow available while the airplane is subjected to normal operational weathering effects and maintenance procedures. The system should, therefore, be capable of surveying the entire wing surface, should be installed in such a manner as to require no structural modifications, and should not adversely affect the performance of the airplane; that is, the device used to check the conditions of the boundary layer should not itself cause transition. In addition, the system should permit continuous monitoring of the condition of the boundary layer with little, if any, attention from the crew during routine service missions and be rugged enough to withstand a certain amount of abuse during routine maintenance of the airplane.

Schemes for determining the boundary-layer condition that are commonly utilized in wind-tunnel research, such as total-pressure probes for measuring the difference between the total pressure in the boundary layer and in the free stream or evaporation techniques for visualizing a difference between laminar and turbulent flow, do not fulfill the desired requirements for flight investigations stated previously.

A possible technique for determining whether the flow in the boundary layer is laminar or turbulent that fulfills these conditions makes use of the difference in heat-transfer characteristics of laminar and turbulent boundary layers. The rate of heat transfer to a turbulent boundary layer is considerably greater than that to a laminar boundary layer. If, therefore, a smooth and faired heated patch could be cemented to, but thermally insulated from, the wing and provisions could be made for measuring the patch temperature, the measured temperature could be used to give an indication of the type of boundary-layer flow. An investigation was made in the Langley low-turbulence pressure tunnel to develop a technique based on this principle and to determine the minimum Reynolds number (per foot) for which such a system of temperature gages would be effective.

SYMBOLS

R'	Reynolds number per foot, V_∞/ν
V_∞	free-stream velocity, ft/sec
ν	kinematic viscosity, sq ft/sec
T_d	temperature of detector, $^{\circ}F$
T_{aw}	adiabatic-wall temperature of airfoil surface at detector, $^{\circ}F$
k	coefficient of thermal conductivity for air, Btu/(sec)(sq ft)($^{\circ}F$)/ft
N_{Pr}	Prandtl number, $c_p \mu g/k$
x	distance from leading edge, ft
$q(x)$	local coefficient of heat transfer at distance x from leading edge, Btu/(sec)(sq ft)($^{\circ}F$)

c_p specific heat at constant pressure, Btu/lb °F

g acceleration due to gravity, ft/sec^2

μ absolute viscosity, slug/ft-sec

APPARATUS AND TESTS

Apparatus

In order to combine the functions of heating and temperature measurement, resistance-thermometer gages were used. Each gage has a filament of very fine nickel wire bonded in a paper and bakelite wafer. A typical resistance-temperature calibration of the gage is given in figure 1. In order to obtain a usable signal when the boundary layer changes from laminar to turbulent, the heat transfer from the gage to the air must be large as compared with the heat transfer from the gage to the adjacent structure. For this reason, the gage was thermally insulated from the wing skin to minimize heat loss to the wing skin; in addition, the insulation facilitated raising the temperature of the gage with respect to the temperature of the boundary layer. As shown in figure 2, the gage was cemented with its smooth side flush with the surface of the bakelite sheet. Extra surface was left around the gage as a land for sanding to avoid damaging the gage during the filling and refairing process. The resulting patch was thick enough for adequate thermal insulation and also for inclusion of the lead wires to the gage. These bakelite patches with the gage cemented in place are hereinafter referred to as "detectors."

For the tunnel tests, eight detectors were arranged on the model shown in figures 3 and 4. The entire wing surface was covered with Fiberglas cloth and Paraplex to the 0.018-inch thickness of the detectors. Cutouts in this covering were made in the desired locations, and the detectors were then cemented to the wing skin so that they were flush with the covering surface. The lead wires were laid in grooves cut in the Fiberglas covering, and the entire surface was refaired as necessary.

The chordwise positioning of the detectors for this investigation was selected so that detectors 1 and 2 would always be in a laminar flow region. Detectors 3 to 6 were placed to observe the forward movement of transition caused by roughness strips located near the leading edge. The roughness strips were located at 2.5 percent chord, and the roughness size was selected to cause transition within the Reynolds number range of each test. The spanwise staggering was such that any unintentional transition that might be caused by any one of the detectors would not influence the flow at adjacent detectors. A photograph of the model with the detectors installed is presented as figure 4, and a closeup of the detector installation is presented as figure 5.

In flight, the effects of ambient temperature and mass-flow changes on the detector temperature are likely to be large in comparison with the effect of boundary-layer transition on the detector temperature. The effects of ambient-temperature and mass-flow changes can be eliminated by having one detector in a known flow and using it as a reference against which the other detectors can be measured. Detector 7 was therefore placed as shown in figure 3 so that it would be within the turbulent wake from the intersection of the model leading edge and tunnel wall and would act as the reference detector. Detector 8 was placed in a similar region (see fig. 3) as a check for detector 7. Of course, on an airplane surface, any desired detector pattern may be used for surveying the condition of the boundary layer inasmuch as the detectors, if properly mounted, should not cause transition.

The electrical circuit was designed to operate from the nominal 27.5-volt d-c aircraft supply with each detector wired as an arm of a Wheatstone bridge circuit. (See fig. 6.) The adjacent arm of the bridge was a fixed 10-ohm resistor. Since the detector resistance is in the order of 100 ohms for the conditions encountered in this investigation, roughly 90 percent of the supply voltage is dropped in the detector. The approximately 6 watts dissipated in this manner raises the detector temperature in still air about 160° F above the ambient temperature when the detector is cemented to the airfoil surface. The temperature of each detector was measured for the power-on zero-flow condition in order to determine the uniformity of the insulation and the approximate operating temperature of each of the detectors. This measurement was made by the use of a half-bridge consisting of a 1,000-ohm resistor and a decade resistance box. (See fig. 6.) As each active half-bridge was switched against this reference, the decade resistance was adjusted for a null reading on the microammeter, and the decade resistance was then a measure of the detector resistance, which is a measure of the detector temperature. These measurements indicated detector temperatures varying from 211° F to 228° F.

In order to measure the difference between several detectors and a reference detector, the circuit shown in figure 6 was used. Each detector with its adjacent arm was treated as a half-bridge and was permanently connected across the power line. A selector switch connected each half-bridge in turn with the half-bridge containing the reference detector, and the unbalance of the resulting bridge gave a measure of the relative temperature of each detector with respect to the reference detector. This circuit keeps power on the detectors continuously and avoids having switch contacts within the bridge circuit. The high input voltage makes the bridge very sensitive, with an output of approximately 5 millivolts per °F difference between two detectors. For the tunnel tests, the bridge unbalance was indicated on a 100-0-100 microammeter. The attenuation was such that the sensitivity was about 2.5 microamperes per °F difference between a detector and the reference detector. The polarity was such that a positive value indicates the detector to be warmer than the reference detector.

Tunnel Tests

The investigation was made in the Langley low-turbulence pressure tunnel at Mach numbers of 0.2 or less, the Reynolds number (per foot) being varied from 0.05×10^6 to 2.8×10^6 by varying the tunnel pressure from 2 inches of mercury absolute to atmospheric pressure. The detectors were mounted on an 85-inch-chord NACA $65_{(215)}$-114 airfoil section (figs. 3 and 4), which completely spanned the 36-inch-wide test section of the tunnel. A description of the tunnel is given in reference 1, and a detailed description of the model, together with airfoil ordinates, is given in reference 2.

The tests were made with the model in the following conditions: (1) a "smooth" condition, except for a rod, 1/8 inch in diameter and 3 inches long, located at 10 percent chord (fig. 4); (2) a rough condition in which the roughness consisted of a strip of No. 60 or No. 120 carborundum grains having a nominal size of 0.011 inch and 0.005 inch, respectively, located at 2.5 percent chord (fig. 7); and (3) a rough condition in which a brass roughness strip having projections of 0.1 inch or greater was placed at 2.5 percent chord (fig. 8).

Environmental and Response Tests

Detectors mounted on a sheet of aluminum alloy were checked at ambient temperatures from about 80° F to -65° F and at pressures from sea level to 65,000 feet. Water was poured over a detector with no apparent effects other than a large temperature drop until the heat evaporated the water from the detector surface. A mounted detector was exposed to the weather on a building roof for two weeks and suffered no apparent effects.

Although knowledge of the dynamic response of the detectors to cyclical variations in cooling was not needed for the present investigation, this information was obtained while checking the detectors and associated instrumentation for adequate sensitivity for use in this investigation and is presented herein. The response of the detector to cyclical variations in cooling was obtained by blowing air over the detectors from a nozzle having a variable-speed rotary mask which provided approximately square-wave pulses over the detector. The response is plotted against frequency in figure 9 and shows that, for this type of detector, the response ratio becomes negligible for frequencies of more than 25 cycles per second.

RESULTS AND DISCUSSION

The results of the tunnel investigation are presented in figures 10 to 13 where microammeter readings are plotted as a function of Reynolds number per foot R' for the various detectors. As stated previously, the polarity of the instrumentation used in this investigation was such that, with the reference detector exposed to a turbulent flow, other detectors exposed to a turbulent flow (equal cooling) showed a reading of approximately zero on the microammeter, while all detectors exposed to a laminar flow (less cooling) showed a positive reading. (See figs. 10 to 13.) Although it might be expected that the microammeter readings for the various detectors, when in the same type of flow, would be the same, figures 10 to 13 show that the readings differ. The difference in readings for detectors in the same type of flow is caused by the difference in operating temperature of the detectors and the difference in local heat-transfer rate with chordwise position, as shown in the following equations for local heat transfer to a laminar boundary layer (ref. 3) and to a turbulent boundary layer (ref. 4), respectively,

$$q(x) = 0.332k\sqrt[3]{N_{Pr}}\sqrt{\frac{R'}{x}}\left(T_d - T_{aw}\right)$$

$$q(x) = 0.024k\left(N_{Pr}\right)^{0.4}\frac{(R')^{0.8}}{x^{0.2}}\left(T_d - T_{aw}\right)$$

Although the combination of these two factors, temperature variation and chordwise position, leads to rather large differences in microammeter readings for detectors in the same type of flow (see figs. 10 to 13), it was not necessary to compensate for their effect inasmuch as the range of Reynolds number for which data were taken simplified the determination of the character of the boundary layer.

For a flight investigation, particularly at high altitude, the Reynolds number R' and the difference in rate of heat transfer to a laminar boundary layer as compared with the heat transfer to a turbulent boundary layer may be small; therefore, it would be desirable to reduce the effect of detector temperature variation and chord position on the microammeter reading. These effects could be reduced, for example, by more careful matching of the insulation on the detectors to assure a more uniform detector temperature and by using a reference detector for each 10 percent of the chord in which measuring detectors are placed.

Figure 10 presents the results for the model in the smooth condition except for a piece of 1/8-inch-diameter rod located at 10 percent chord to assure turbulent flow over the reference detector (see fig. 4). The data of figure 10 show that detectors 1 to 6 indicate a laminar flow over the central portion of the model, whereas the flow over detector 8 is apparently turbulent. The turbulent flow over detector 8 was undoubtedly the turbulent wake from the intersection of the model leading edge and tunnel wall (fig. 3); and, inasmuch as detector 7 was in a similar field of flow, the 1/8-inch-diameter rod was removed for subsequent tests.

The results for the model with No. 120 carborundum roughness and No. 60 carborundum roughness are presented in figures 11 and 12, respectively. In these two figures, the thermal detectors appear to be satisfactory for determining the character of the boundary layer, at least for Reynolds number R' as low as 0.3×10^6.

Transition is shown in figures 11 and 12 by the sudden change in meter readings for an individual detector; and, in general, the Reynolds number for transition as shown by the detectors is in reasonably good agreement with the data of reference 5. In figure 11 the Reynolds number R' for transition for detectors 3 and 4 is lower than was expected; however, an examination of the model showed the roughness forward of these detectors to be somewhat larger than the nominal 0.005 inch for No. 120 carborundum. For this reason, transition would be expected to occur at a somewhat lower Reynolds number. The slight difference in meter reading for the detectors at the same Reynolds number but different pressures (fig. 11) is due to small variations in battery voltage.

The primary point of interest in figure 12 is that, as the Reynolds number R' is reduced below about 0.3×10^6, the microammeter reading approaches zero for all detectors. This would indicate that either the flow over the reference detector and detector 8 had become laminar or that the difference in heat transfer to a laminar boundary layer, as compared with a turbulent boundary layer, is so small at this Reynolds number that the system as used in this investigation could not measure it. However, the addition of a brass roughness strip (fig. 8) with projections of 0.1 inch or more forward of detectors 5 to 7 showed (fig. 13) that the flow over detector 8 did change from turbulent at $R' = 0.3 \times 10^6$ to laminar at $R' = 0.15 \times 10^6$ and indicated that, at this low Reynolds number, natural transition did not occur at the intersection of the model leading edge and tunnel wall. Figure 13 also shows that for the instrumentation used in this investigation, the minimum Reynolds number for which the thermal detectors have sufficient sensitivity to determine the character of the boundary layer appears to be approximately 0.15×10^6.

APPLICATION OF RESULTS TO FLIGHT TESTS

Inasmuch as the present investigation was conducted in a wind tunnel, there remains the question as to whether the boundary-layer heat-transfer characteristics of this investigation are similar to those which would be expected in a flight investigation. In order to answer this question, it is necessary to examine the equations for local heat transfer and to determine the factors therein which might vary for any other investigation in air. The equations for local heat transfer to a laminar and to a turbulent boundary layer are given previously but are repeated for convenience.

The local heat transfer to a laminar boundary layer is given by the following equation:

$$q(x) = 0.332k\sqrt[3]{N_{Pr}}\sqrt{\frac{R'}{x}}\left(T_d - T_{aw}\right)$$

The local heat transfer to a turbulent boundary layer is given by the following equation:

$$q(x) = 0.024k\left(N_{Pr}\right)^{0.4}\frac{(R')^{0.8}}{x^{0.2}}\left(T_d - T_{aw}\right)$$

An examination of the factors in these equations shows that k and N_{Pr} are constants for air, R' and x are functions of airplane size, speed, and altitude, and $\left(T_d - T_{aw}\right)$ is a function of the power supplied to the detectors and the insulation between the wing surface and the detectors. Therefore, with k and N_{Pr} as constants, R', x, and $\left(T_d - T_{aw}\right)$ are the only factors which must be considered when determining whether the conditions for heat transfer to a boundary layer in another investigation is the same as in this investigation.

In the present investigation, x varied from 8.5 inches to 34 inches, R' varied from 0.05×10^6 to 2.8×10^6, $\left(T_d - T_{aw}\right)$ was about 160° F for the zero-flow condition, and, at $R' = 2.0 \times 10^6$, $(T_d - T_{aw})$ was about 140° F in laminar flow and about 120° F in turbulent flow. Since $(T_d - T_{aw})$ is fixed by the insulation and power supplied to the detector and the adiabatic-wall temperature at the detectors T_{aw} is fixed by the stream conditions, the maximum Mach number for which these detectors may be used is limited by the maximum allowable temperature of the resistance element in the detector. The maximum allowable temperature of the resistance elements used in the present investigation was about 400° F; therefore, the limiting Mach number for the detectors used herein would be about 2.0.

In order to convey a clearer impression of how the range of unit Reynolds numbers of this investigation $(0.05 \times 10^6$ to $2.8 \times 10^6)$ would compare with those for a possible flight investigation, figure 14 was prepared. Figure 14 presents Reynolds number R' for an airplane flying at a Mach number of 1.0 as a function of altitude and shows that the range of unit Reynolds number of this investigation is the same as the range for an airplane flying at a Mach number of 1.0 at altitudes from 30,000 to well over 100,000 feet.

In order to permit continuous and unattended monitoring of the wing boundary layer during routine flights, a motor-driven selector switch could be used in conjunction with recording instruments such as a recording galvanometer of the type used in the NACA VGH recorder (ref. 6). This instrument is particularly suitable inasmuch as it provides long record time and allows recording airspeed and altitude on the same record.

CONCLUDING REMARKS

A thermal system has been developed which could be used to determine whether the boundary layer on a wing in flight is turbulent or laminar. Tests were made of this system in the Langley low-turbulence pressure tunnel. While these tests were of a somewhat preliminary nature, they did show that temperature gages of the type used in this investigation can be used to differentiate between a laminar boundary layer and a turbulent boundary layer at Reynolds numbers per foot as low as about 0.15×10^6 and that probably even lower Reynolds numbers would be practical, if the sensitivity of the detectors were increased and the effect of chordwise position and variation in operating temperature of the detectors were reduced. The sensitivity of the detectors could be increased by raising the operating temperature, and the effect of temperature variations and chordwise position could be reduced by more careful matching of the insulation and the use of additional reference detectors, respectively.

For a flight investigation, particularly at low Reynolds numbers, the unavoidable differences in operating temperature due to slight differences in insulation may be larger than the differences to be measured; therefore, it would probably be desirable to make a check flight with sufficient artificial roughness forward of each detector to insure turbulent flow. By so doing, a base level for each detector with respect to a reference detector would be established. However, if the differences in operating temperature due to mismatching are less than the temperature differences to be measured, the record can be interpreted directly without the necessity of plotting differences with and without roughness.

Some further work might be devoted to the fabrication of the detector. The type used in this investigation worked satisfactorily but was somewhat difficult to make. If the detectors could be built into a patch by some molding technique, it should be easier to obtain a more uniform thickness of insulation and a smoother surface. In addition, experience with the test installation indicates that a more uniform cement thickness and, therefore, closer thermal matching would be obtained by cementing the detectors to the airplane surface first and then filling around them afterwards.

The Fiberglas and Paraplex used for filling around the detectors appeared to be satisfactory, and, for the thickness used, the added weight was only about 0.2 pound per square foot. A rubber-base paint presently used on aircraft was tried on a sample installation; however, because of the detector thickness several coats were necessary, and it appeared that subsequent shrinkage would cause trouble. No other materials were investigated at this time. Inasmuch as the gages, resistors, and voltage supply used were selected primarily on the basis of availability, no inference should be made that this specific combination would give the best possible performance.

In order to permit continuous and unattended monitoring of the wing boundary layer during routine flight, a recording instrument such as the galvanometer in an NACA VGH recorder could be used in conjunction with a motor-driven selector switch.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., July 5, 1957.

REFERENCES

1. Von Doenhoff, Albert E., and Abbott, Frank T., Jr.: The Langley Two-Dimensional Low-Turbulence Pressure Tunnel. NACA TN 1283, 1947.

2. Quinn, John H., Jr.: Drag Tests of an NACA $65_{(215)}$-114, a = 1.0 Practical-Construction Airfoil Section Equipped With a 0.295-Airfoil-Chord Slotted Flap. NACA TN 1236, 1947.

3. Schlichting, Hermann (J. Kestin, trans.): Boundary Layer Theory. McGraw-Hill Book Co., Inc., 1955, pp. 256-258.

4. McAdams, William H.: Heat Transmission. Third ed., McGraw-Hill Book Co., Inc., 1942, pp. 165-183.

5. Von Doenhoff, Albert E., and Horton, Elmer A.: A Low-Speed Experimental Investigation of the Effect of a Sandpaper Type of Roughness on Boundary-Layer Transition. NACA TN 3858, 1956.

6. Richardson, Norman R.: NACA VGH Recorder. NACA TN 2265, 1951.

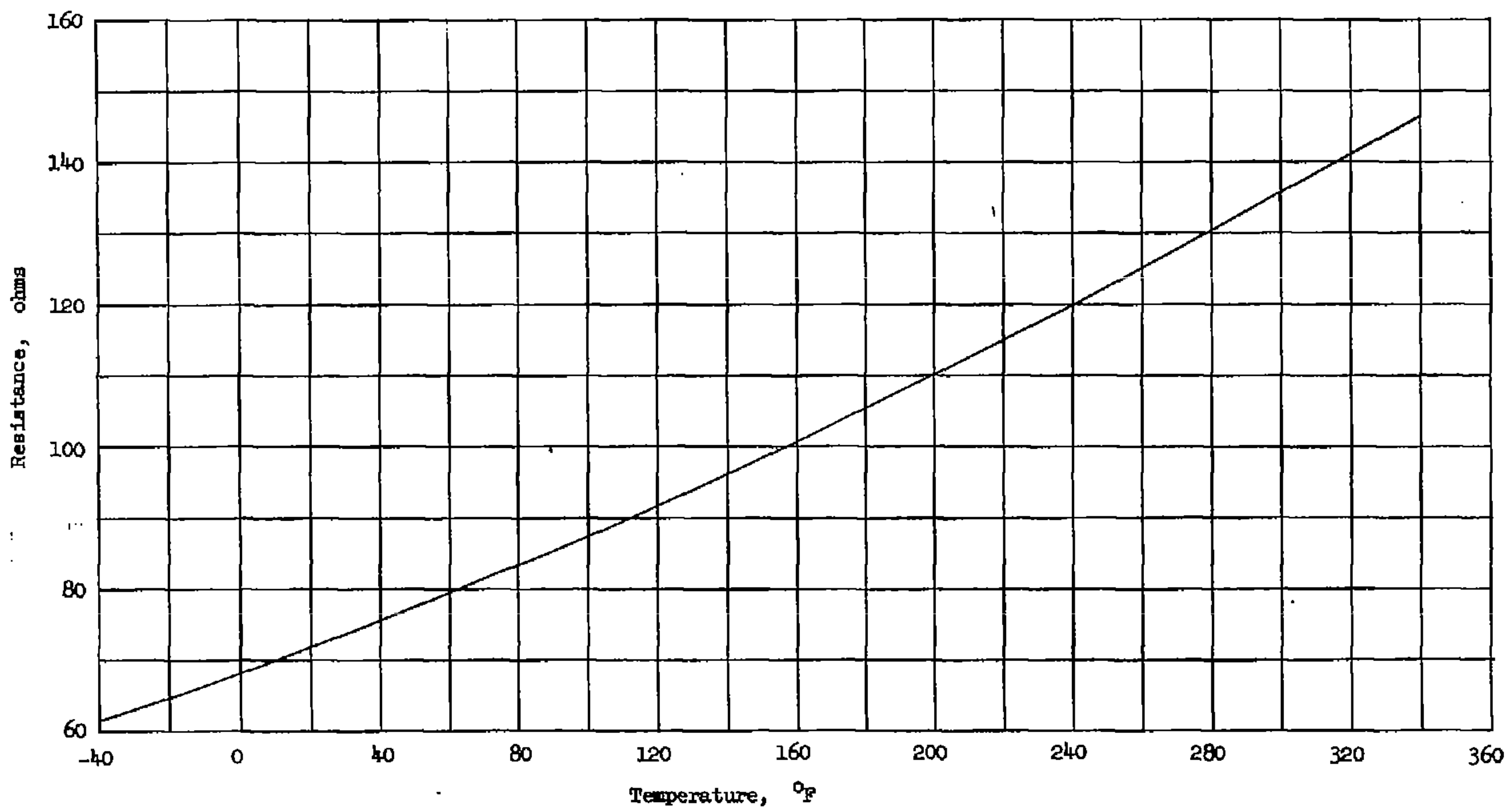


Figure 1.- Calibration of typical resistance thermometer.

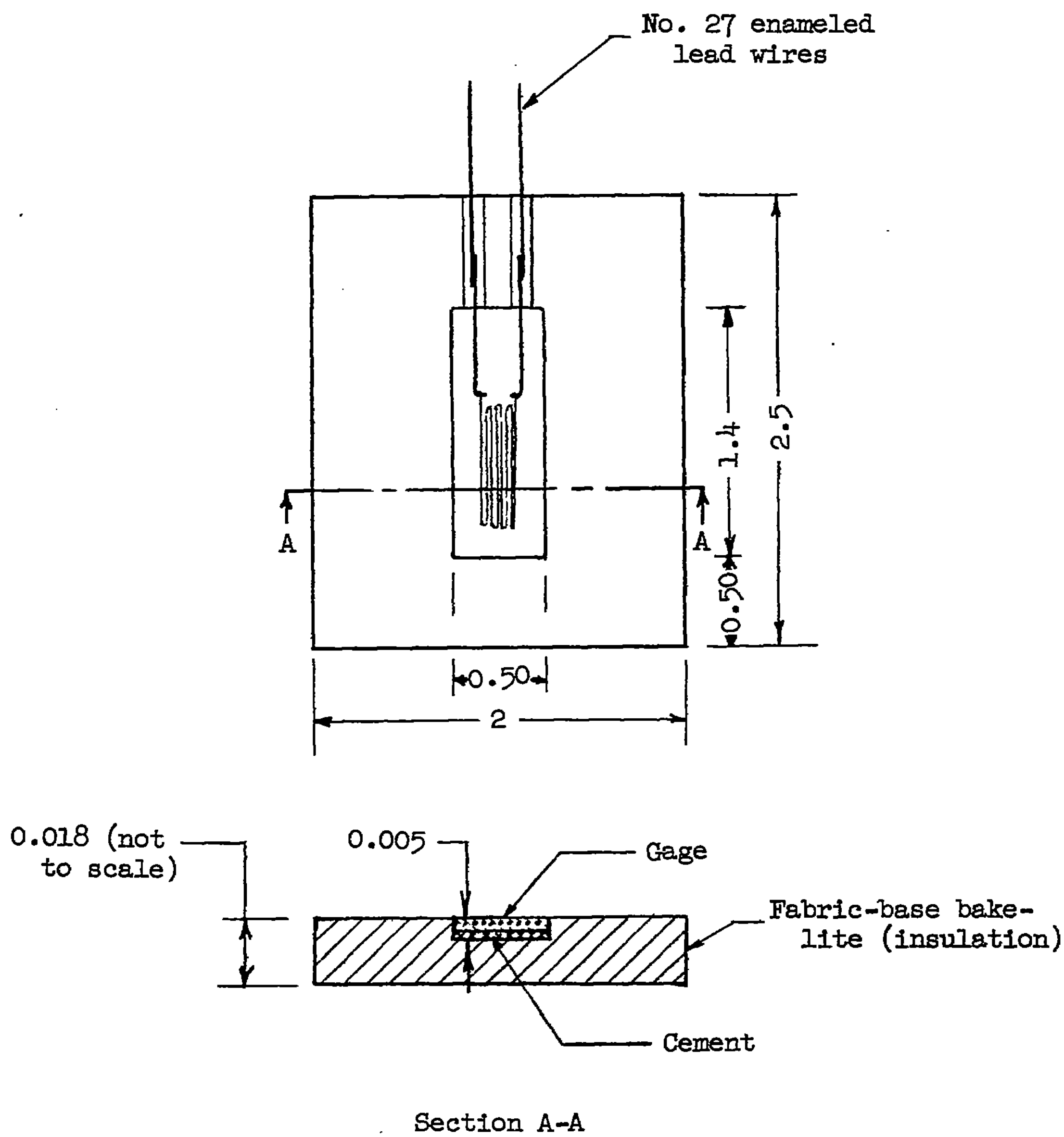


Figure 2.- Details of detector. All dimensions are in inches.

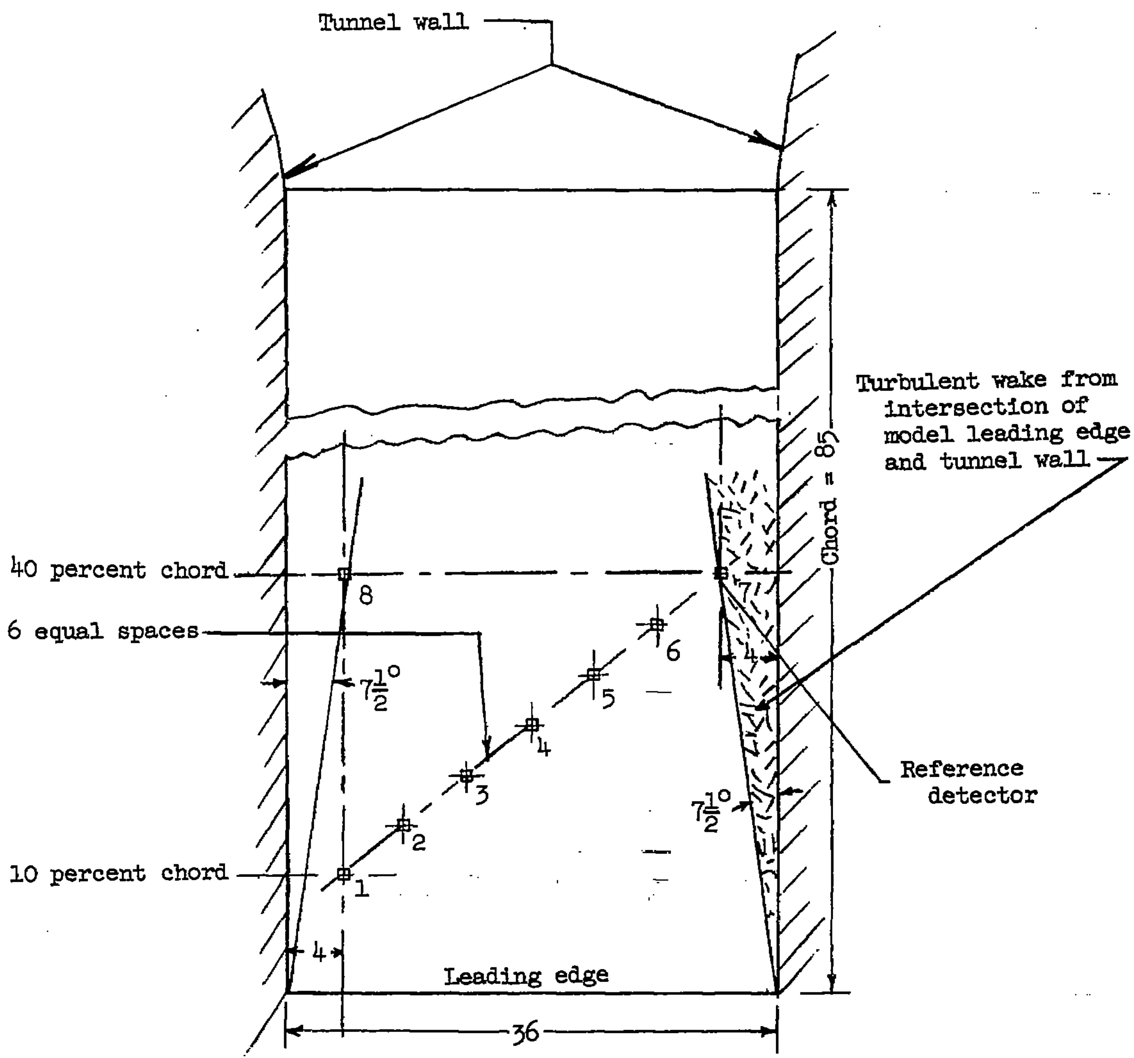
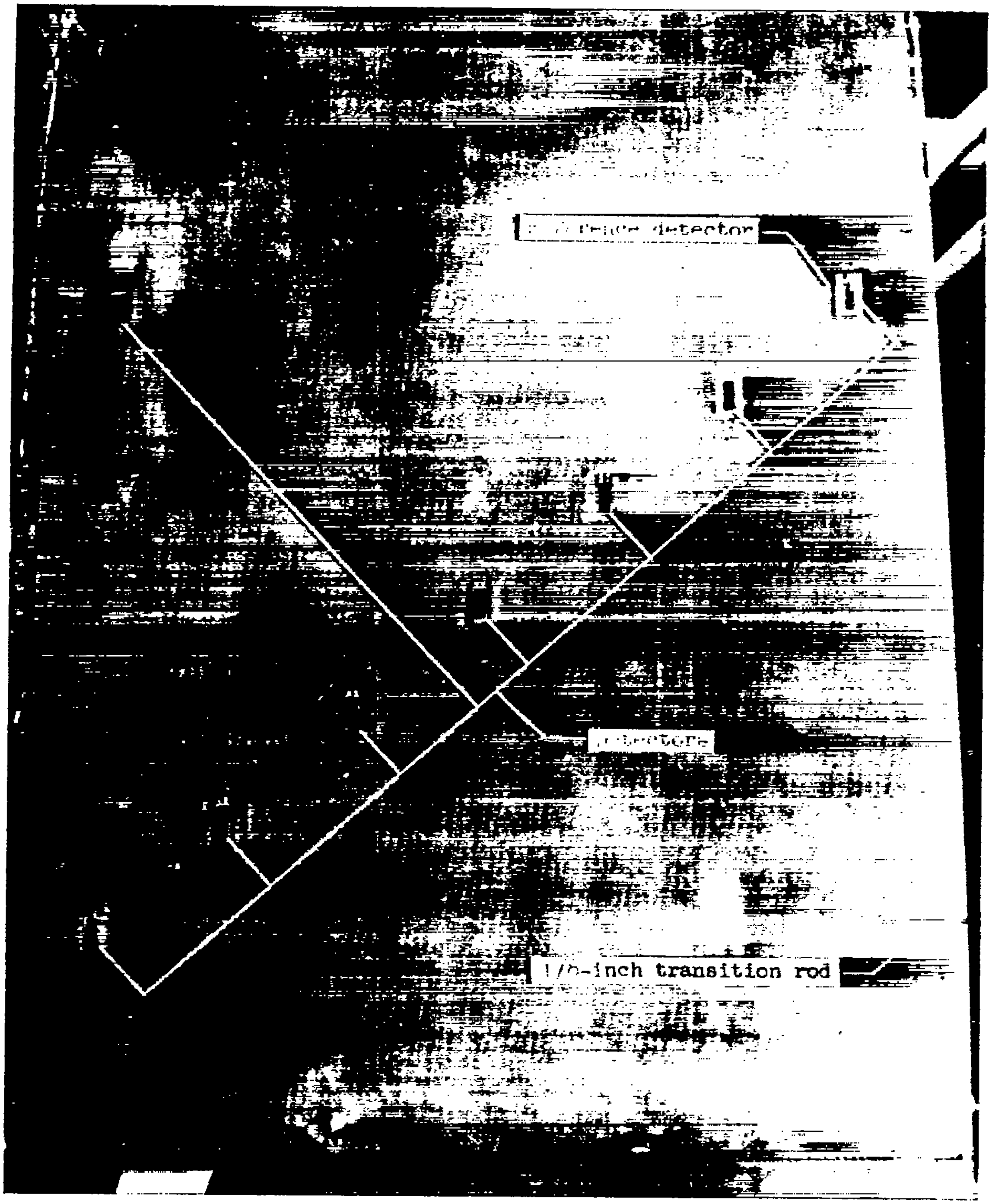
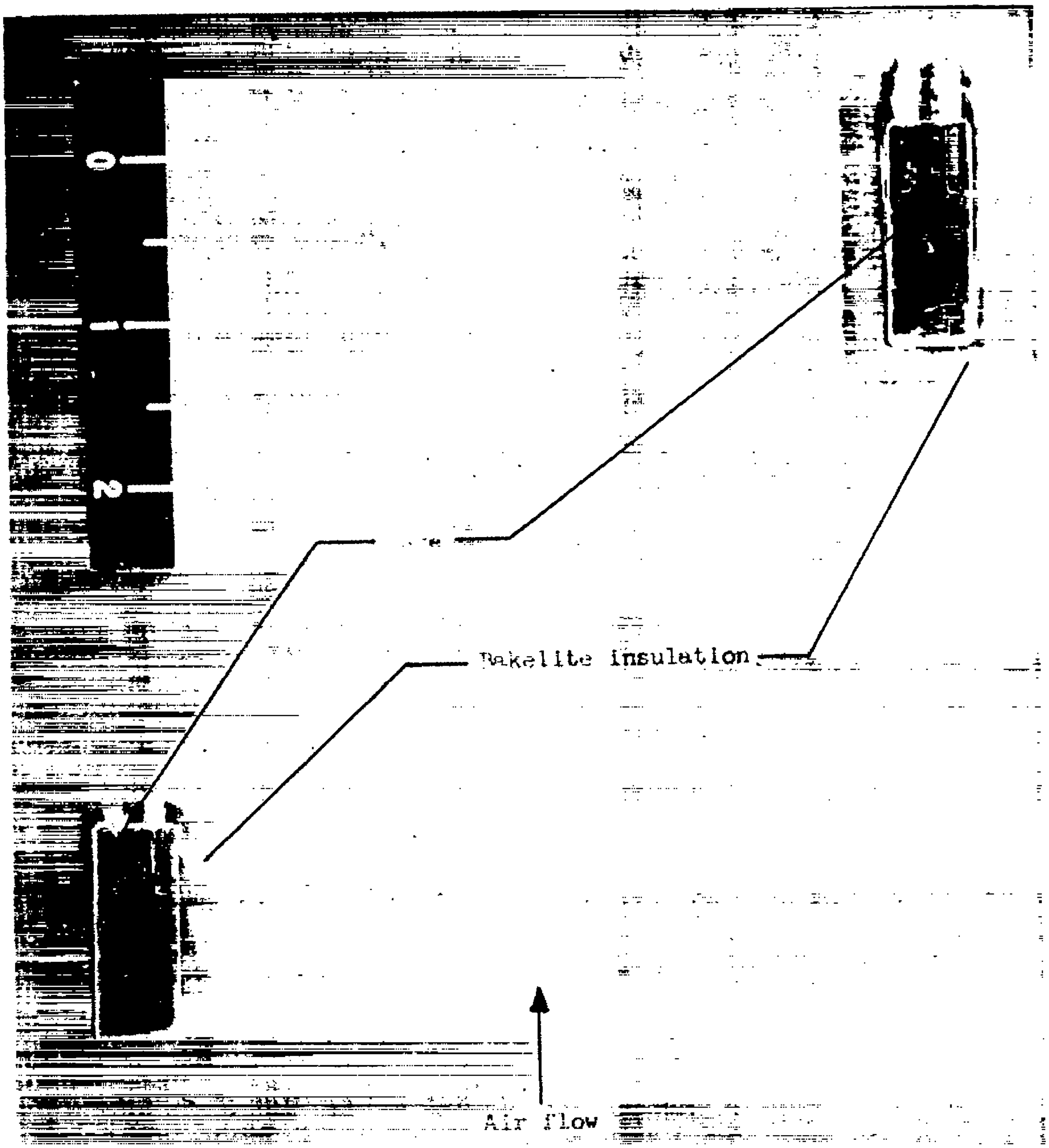


Figure 3.- Layout of detectors on upper surface of model. All dimensions are in inches.



L-97013.1

Figure 4.- Top view of model with detectors and 1/8-inch transition rod in place.



L-92793.1

Figure 5.- Closeup of detector installation. Scale in inches.

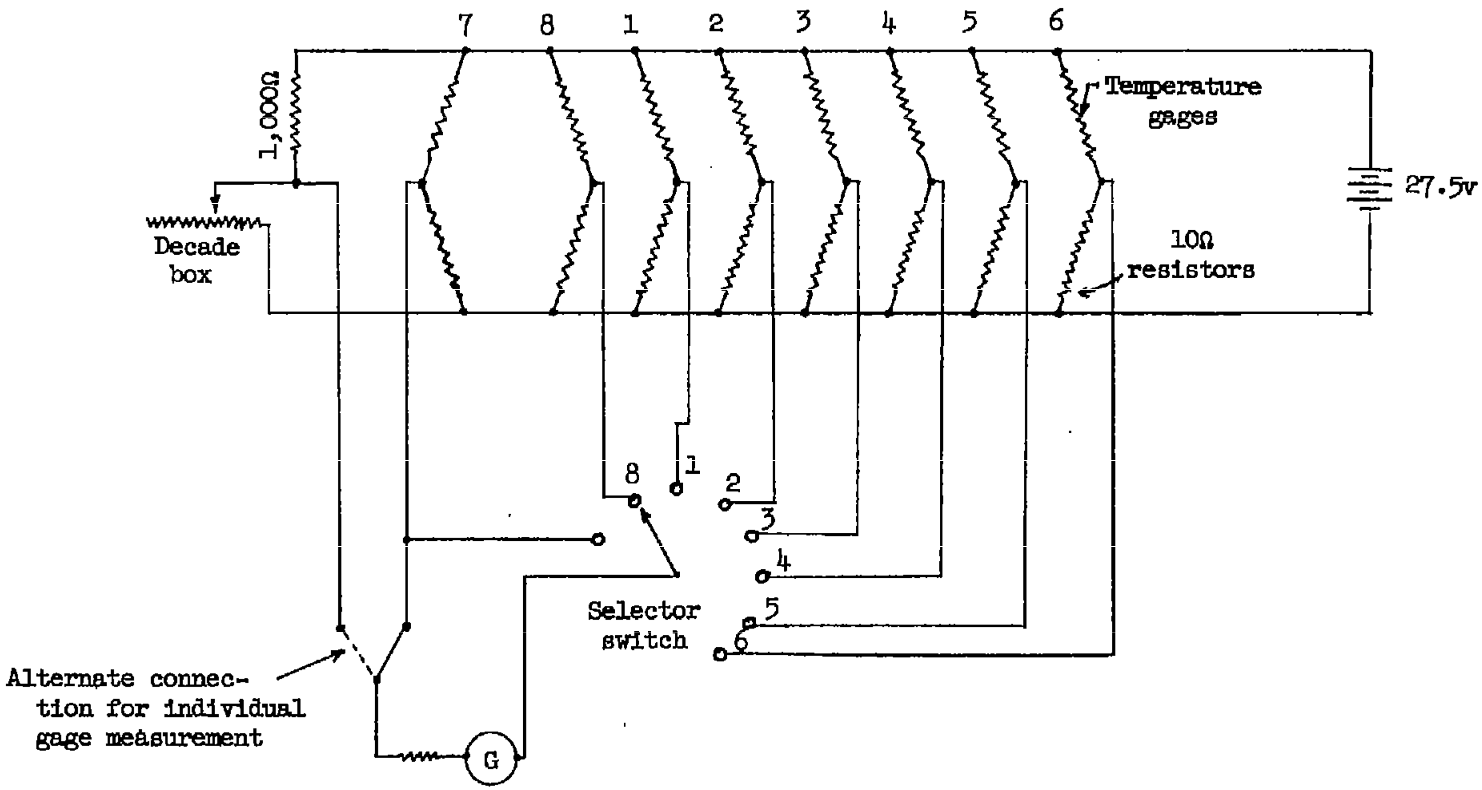
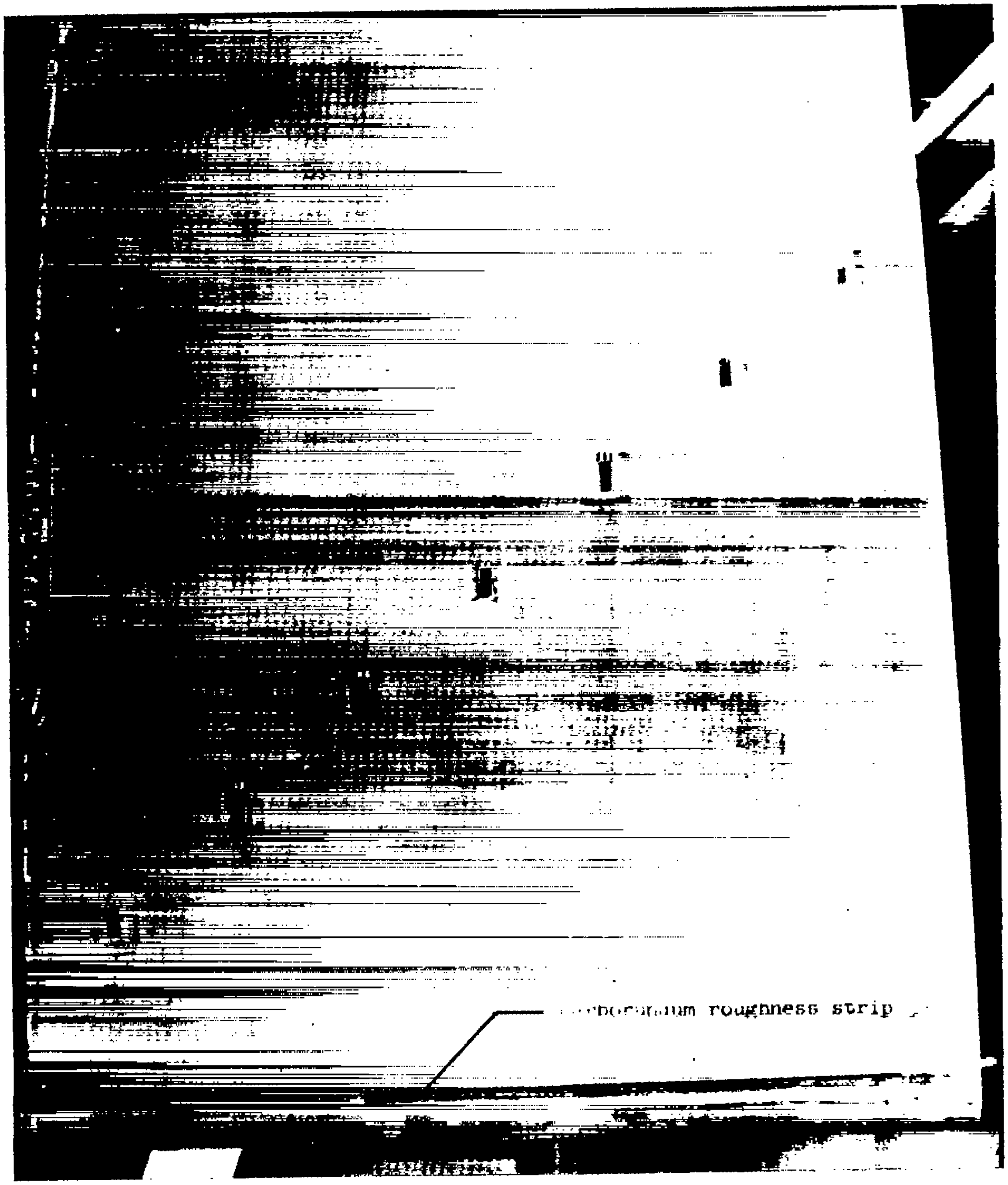


Figure 6.- Electrical circuit for individual or difference readings.



L-97014.1

Figure 7.- Top view of model showing location of carborundum roughness strip.

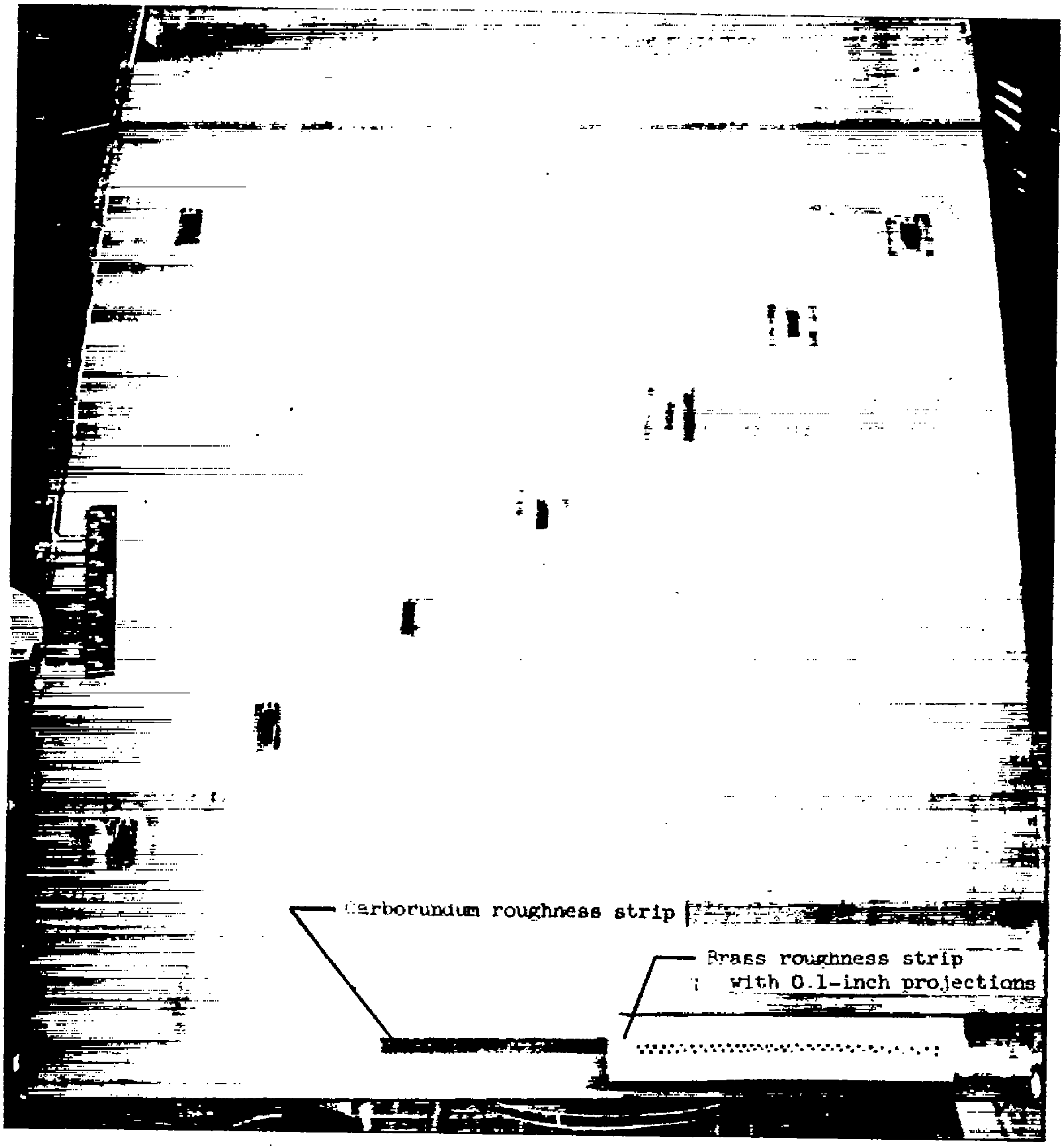


Figure 8.- Top view of model showing brass roughness strip. L-92792.1

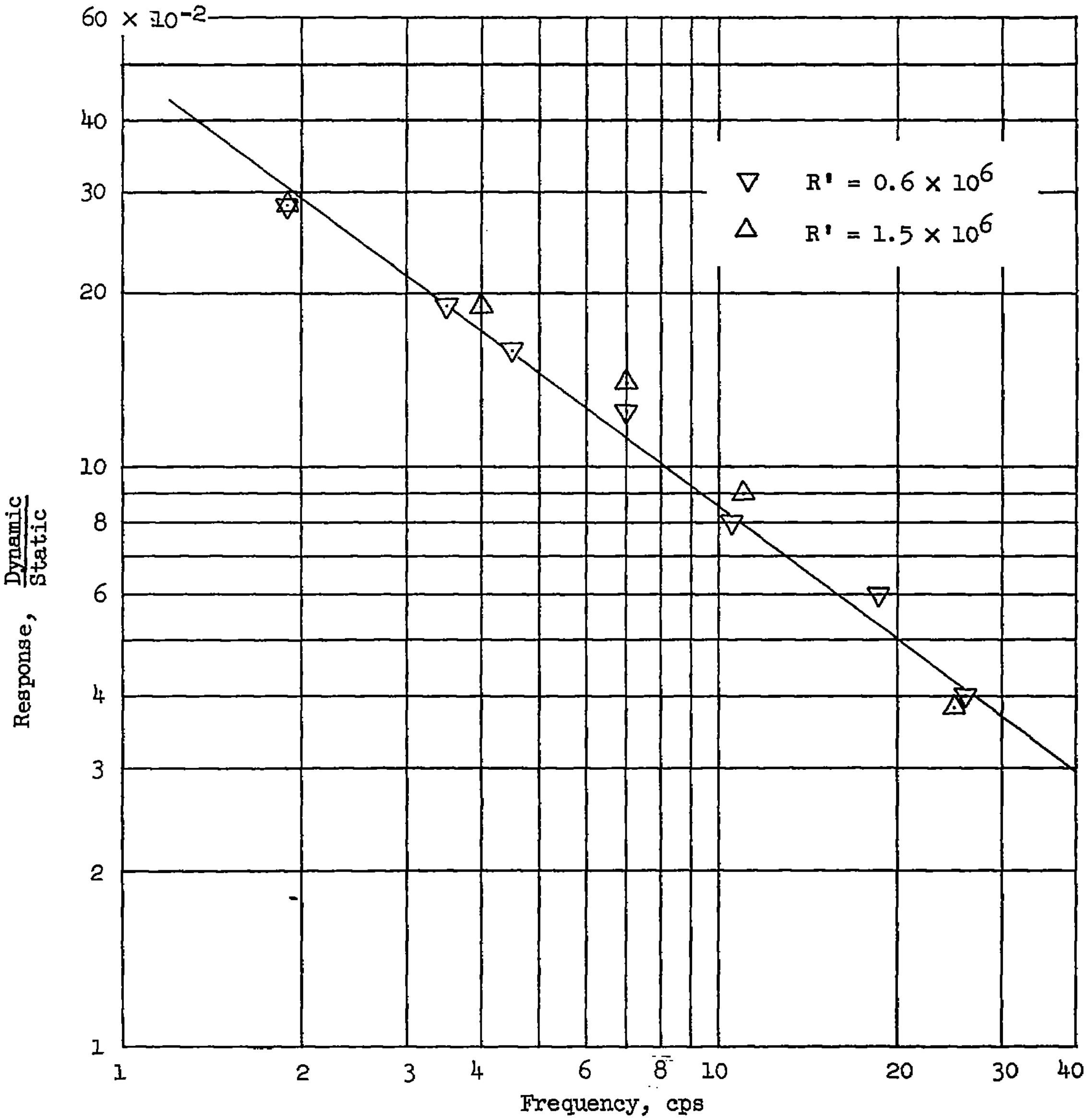


Figure 9.- Response of detector to approximately square-wave input.

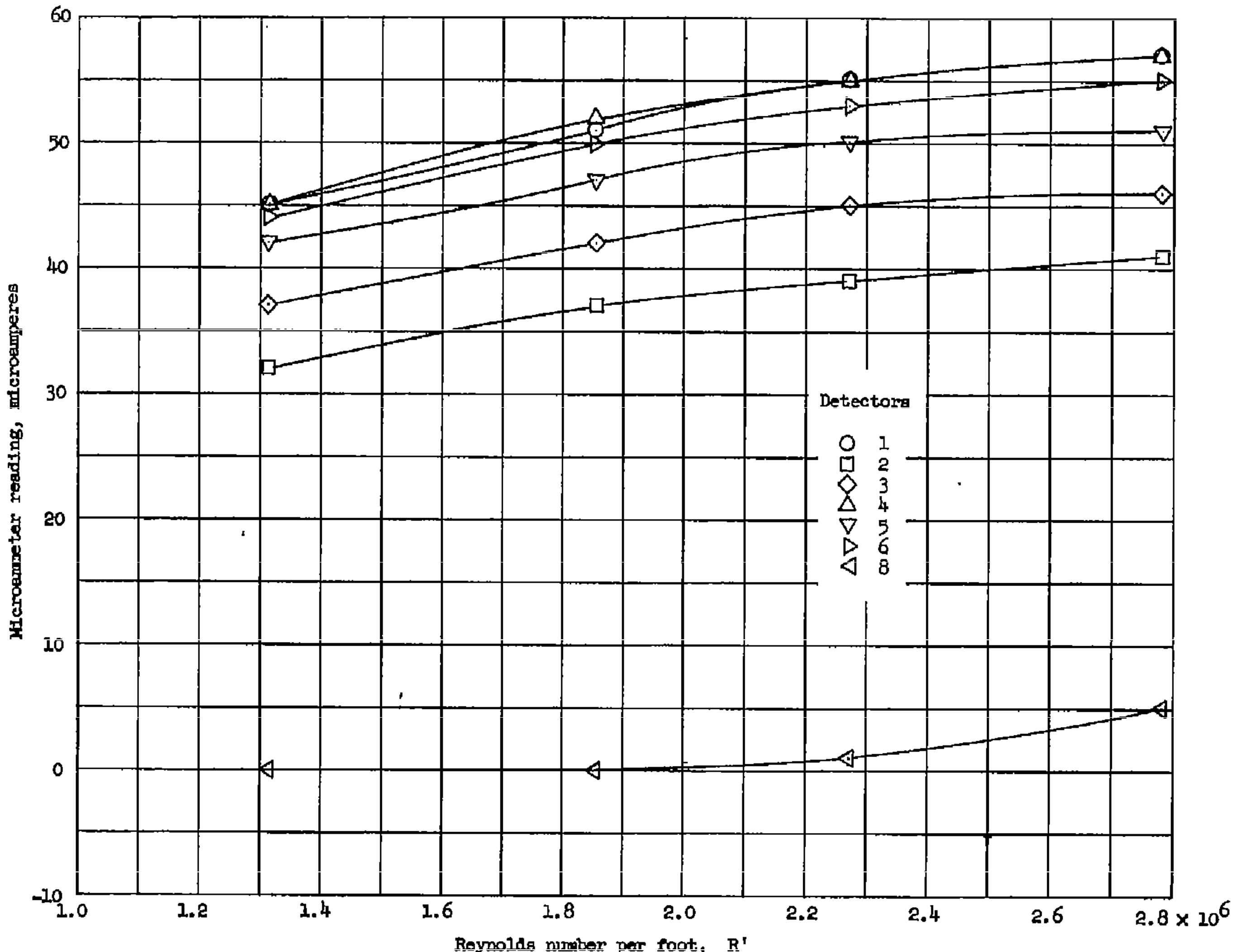


Figure 10.- Microammeter reading as a function of Reynolds number R' for model in smooth condition except for 1/8-inch rod forward of detector 7.

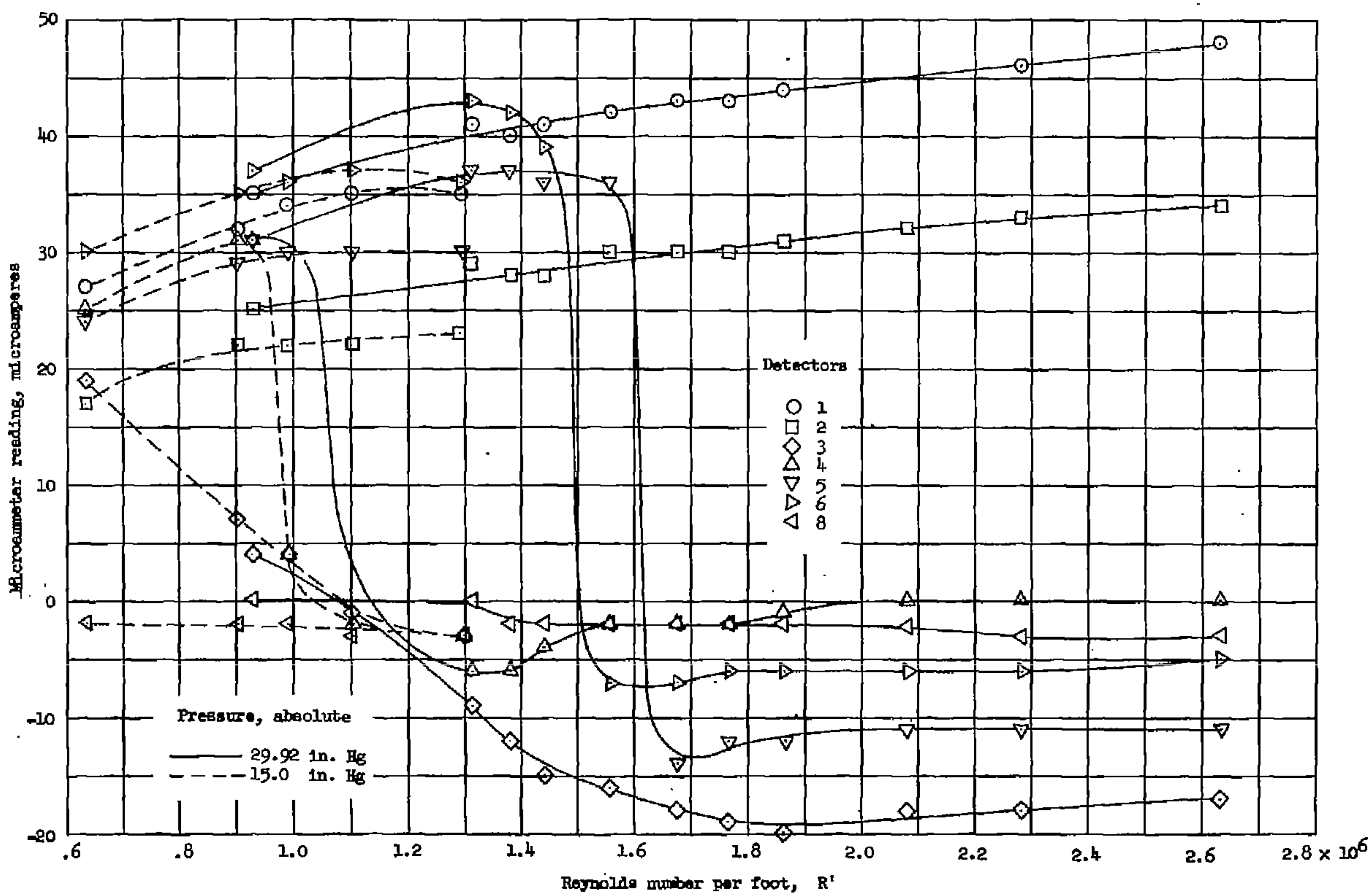


Figure 11.- Microammeter reading as function of Reynolds number R' for model with No. 120 (0.005-inch) carborundum grains forward of detectors 3 to 7.

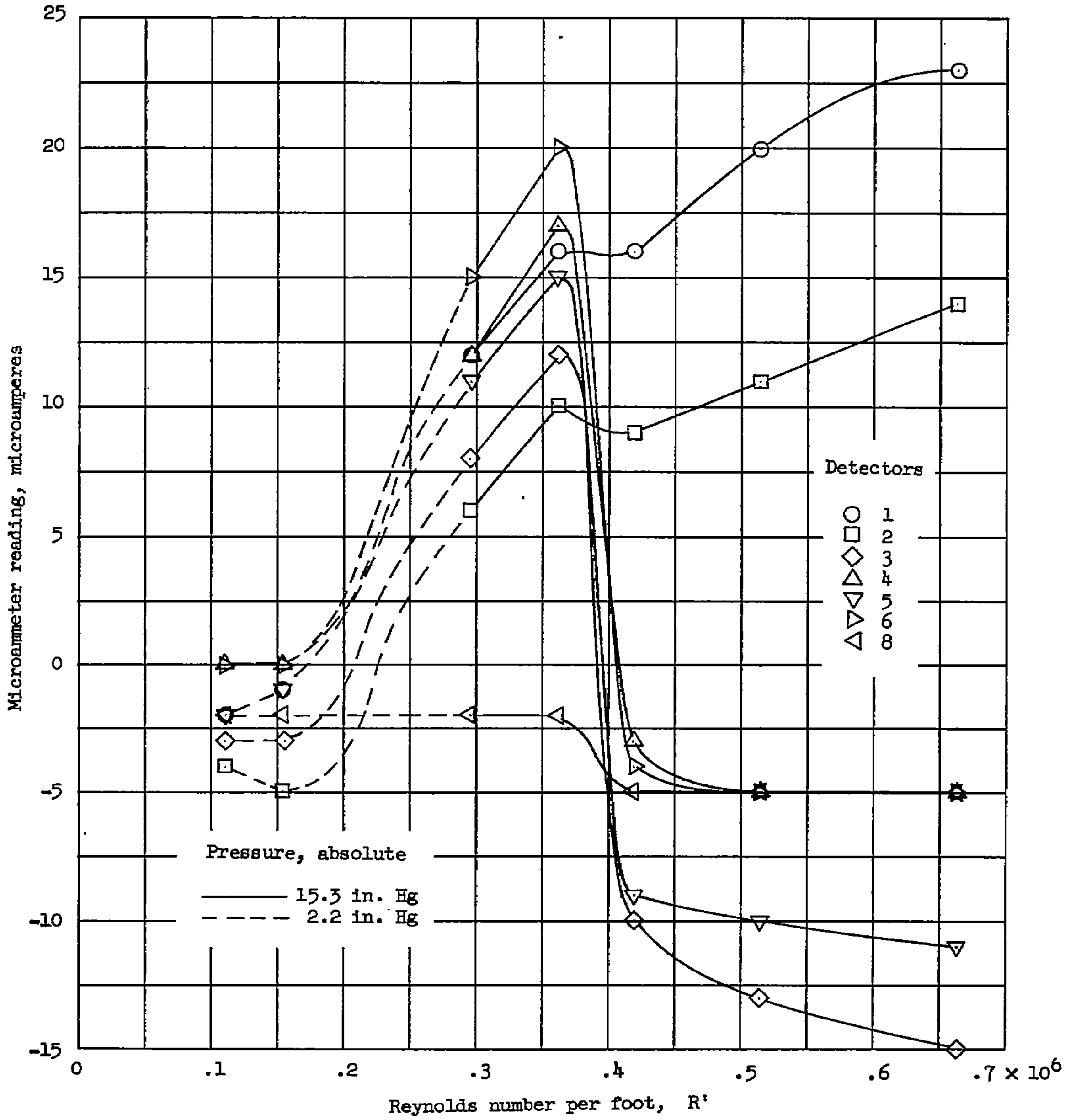


Figure 12.- Microammeter reading as function of Reynolds number R' for model with No. 60 (0.011-inch) carborundum grains forward of detectors 3 to 7.

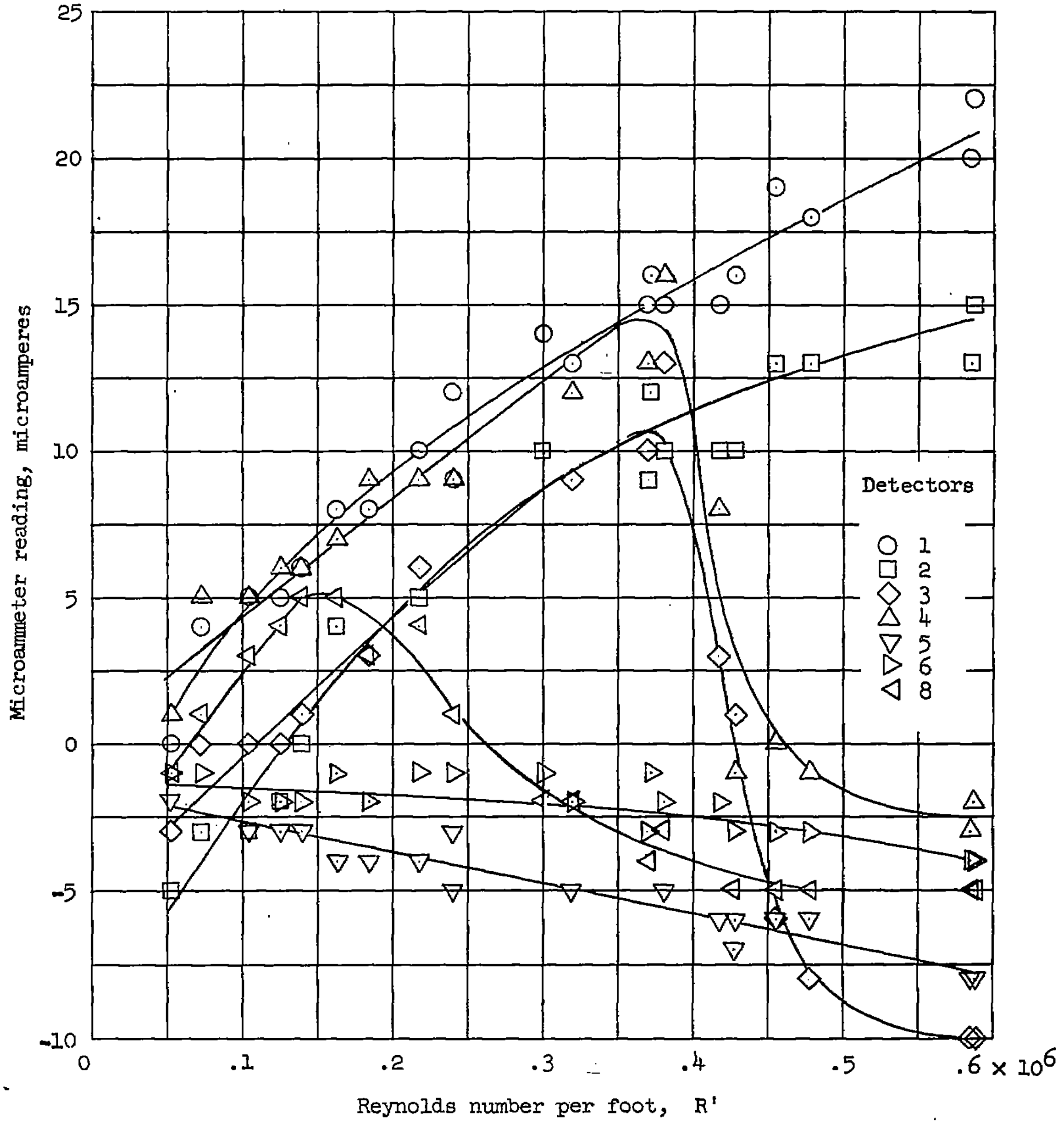


Figure 13.- Microammeter reading as function of Reynolds number R' for model with No. 60 (0.011-inch) carborundum grains forward of detectors 3 and 4 and brass roughness strip forward of detectors 5 to 7.

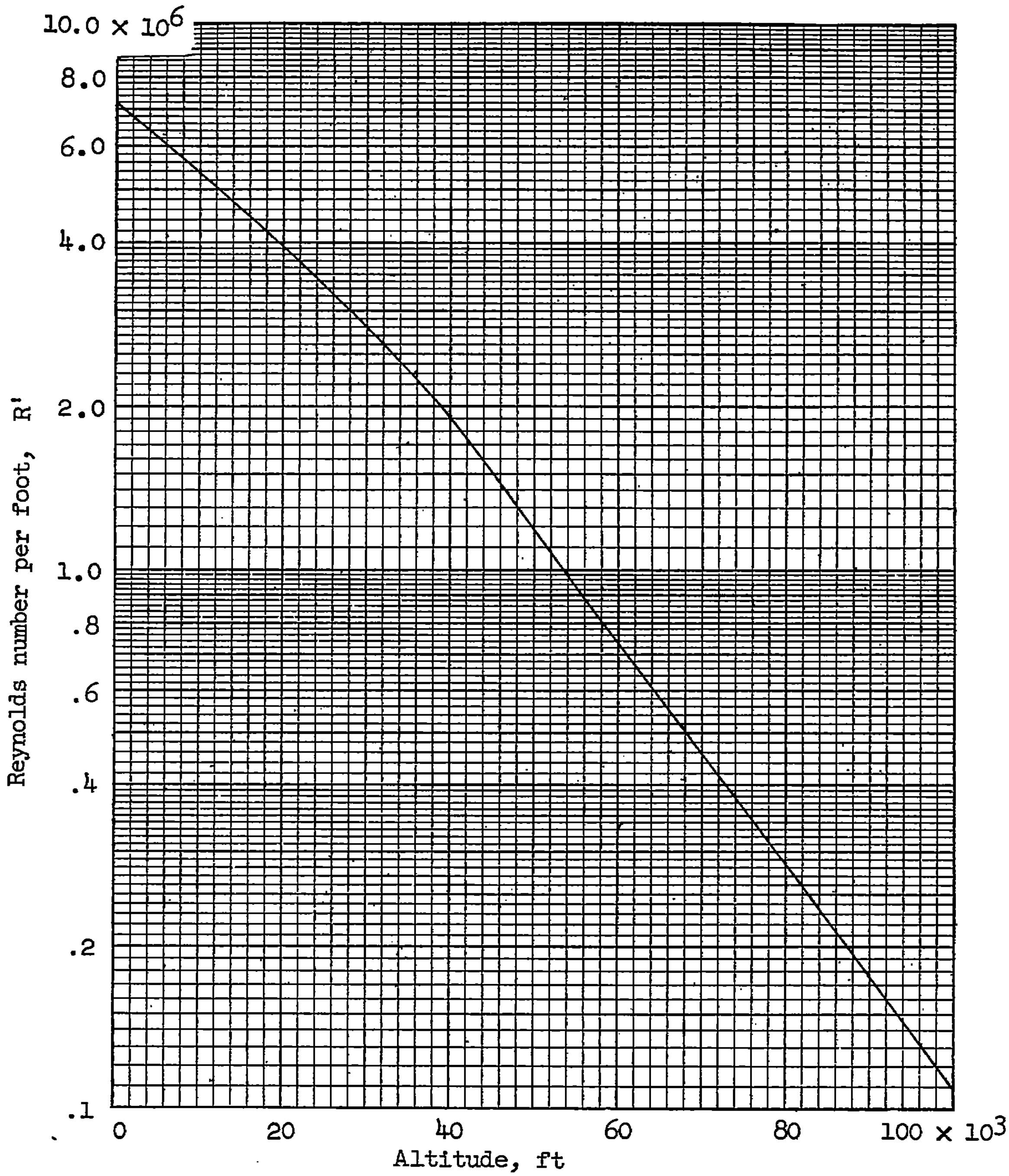


Figure 14.- Reynolds number R' as function of altitude for Mach number of 1.0.